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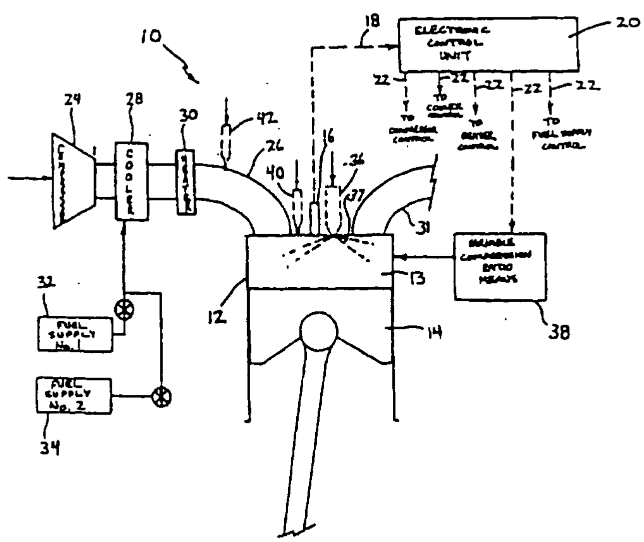

(57) Abstract

An improved HCCI engine and control scheme is provided which produces stable HCCI combustion while optimally minimizing emissions and maximizing efficiency. In the present invention, the fuel/air mixture is thoroughly mixed to form a very lean homogeneous mixture, or is mixed in a manner to form a desired air/fuel stratification, to ensure relatively even, low flame temperatures which result in extremely low NOx emissions. The control system senses the start of combustion, the combustion rate and/or the combustion duration and, based on the sensed condition, actively controls the temperature, pressure, equivalence ratio and autoignition properties to continuously maintain optimum combustion.

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HOMOGENEOUS CHARGE COMPRESSION IGNITION ENGINE WITH OPTIMAL COMBUSTION CONTROL

BACKGROUND OF THE INVENTION

This invention relates generally to a homogeneous charge compression ignition (HCCI) engine, that is, an engine arranged to internally burn a homogeneous mixture of fuel and air using autoignition. HCCI engines have no simple way of controlling the start of combustion and the rate of combustion. This is very different from a diesel engine or a spark ignited engine. In the diesel engine, start of combustion is controlled by the timing of fuel injection. In a spark ignited engine, the start of combustion is controlled by the spark timing.

The concept of operating an internal combustion engine using HCCI principles has been disclosed. For example, U.S. Patent No. 4,768,481 to Wood discloses a process and engine that is intended to use a homogeneous mixture of fuel and air which is spontaneously ignited. A controlled rate of combustion is said to be obtained by adding exhaust products to the air-fuel mixture. The patent to E. Inventor (U.S. Patent No. 5,476,072) discloses another example of an HCCI engine having a cylinder head design that prevents excessive stresses and structural damage that HCCI engines inherently tend to cause. Still other HCCI engine concepts are disclosed in the following articles:

Thring, R., "Homogeneous-Charge Compression Ignition (HCCI) Engines," SAE Technical Paper Series 892068, September 25, 1989.

Aoyama, T. et al., "An Experimental Study on Premixed-Charge Compression Ignition Gasoline Engine," SAE Technical Paper Series 960081, February 26, 1996.

Ishibashi, Y. et al., "Improving the Exhaust Emissions of Two-Stroke Engines by Applying the Activated Radical Combustion," Society of Automotive Engineers, Paper No. 960742, 1996.

Despite the concepts disclosed in the prior art, no practical HCCI engine is presently available.

SUMMARY OF THE INVENTION

A general objective of the subject invention is to overcome the deficiencies of the prior art by providing a practical design for forming and operating an HCCI engine. In particular, applicants have recognized that the key to producing a viable HCCI engine lies in the control of the start of combustion and the combustion rate in such a manner so as to result in extremely low NOx emissions combined with very good overall efficiency, combustion noise control and with acceptable cylinder pressure. The present invention is directed to an improved HCCI engine and control scheme for controlling the engine in a manner to optimally minimize emissions while maximizing efficiency. In the present invention, the fuel/air mixture is thoroughly mixed to form a very lean homogeneous mixture, or is mixed in a manner to form a desired air/fuel stratification, to ensure relatively even, low flame temperatures which result in extremely low NOx emissions.

Applicants have conducted tests using a single cylinder research engine operating as an HCCI engine which have demonstrated NOx emission levels that are well below any other NOx emission levels ever demonstrated by applicants using diesel and natural gas engines, and well below future emissions standards.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic diagram of an embodiment of the subject invention.

DETAILED DESCRIPTION OF THE INVENTION

FIG. 1 illustrates the HCCI system of the present invention, indicated generally at 10, as applied to a single engine cylinder 12 which forms a combustion chamber 13. Of course, HCCI system 10 would typically be used to control combustion in a multi-cylinder internal combustion engine. The HCCI system of the present invention may, however, be used on any internal combustion engine having compression, combustion and expansion events, including a rotary engine. In the engine of FIG. 1, a piston 14 is reciprocally mounted in the cylinder for transmitting forces generated by a combustion event into a conventional engine drive system. The HCCI system 10 includes a combustion sensor 16 for sensing the commencement of combustion and/or the rate of combustion and generating a corresponding signal 18. Also, an electronic control unit 20 (ECU) is provided to receive the signal 18 and generate a plurality of output signals, indicated at 22, for variably controlling respective components of the system so as to effectively ensure the commencement of combustion and completion of combustion between 20 degrees BTDC during the compression stroke and 35 degrees ATDC during the power stroke of the piston thereby minimizing NOx emissions while maximizing engine efficiency.

As discussed herein, HCCI system 10 may include various components for optimizing the combustion event. The objectives of the present system, i.e. low NOx emissions, high efficiency, etc, may be achieved using any one of the various control components, or any combination of the components. In particular, a compressor 24 may be provided along an intake duct 26 for varying the boost intake pressure. A cooler 28 may also be provided downstream of compressor 24. Also, a heater 30

(such as a burner) may be provided along intake duct 26, for example, after cooler 28 as shown in FIG. 1, or alternatively, upstream of compressor 24. Compressor 24, cooler 28 and heater 30 each include control devices for varying the effect of the particular component on the pressure/temperature of the intake air or mixture. For example, if the compressor were driven by exhaust gases, a bypass valve or waste gate could be used to regulate the amount of exhaust gas supplied from an associated exhaust system, which is connected to an exhaust duct 31, to compressor 24 thereby varying the intake pressure as desired. Similarly, a control valve could be provided in the cooling fluid flow path supplied to cooler 28 to permit variable control of the cooling effect of cooler 28. Likewise, various types of variable controls could be used to vary the heating effect of heater 30. Output signals 22 from ECU 20 are supplied to the various control devices to control compressor 24, cooler 28 and heater 30 so as to variably control the pressure and temperature of the intake air or mixture on a cycle-by-cycle basis.

In addition, as noted herein, the HCCI system 10 may include a plurality of fuel supplies 32 and 34 for supplying fuels having different autoignition properties (for example, different octane or methane ratings, or activation energy levels) to the intake duct 26. For example, fuel may be supplied along intake duct 26 at cooler 28. The present HCCI system 10 also importantly includes a variable compression ratio means 38 for varying the compression ratio so as to advantageously advance or retard the combustion event as desired. For example, variable compression ratio means 38 may be in the form of a control mechanism for varying the shape of the combustion chamber to vary the effective compression ratio. The effective compression ratio could also be varied by varying the valve timing. In addition, in-cylinder diluent injection may be accomplished using an injector 40 for injecting a gas or liquid, i.e. air, nitrogen, carbon dioxide, exhaust gas, water, etc., into the cylinder to vary the temperature and the temperature distribution in the cylinder so as to control the

combustion event. Similarly, a diluent may be injected into intake duct 26 using, for example, an injector 42.

The present HCCI system may also include a fuel injector 36 for injecting fuel 37, e.g. diesel fuel, directly into the combustion chamber. Fuel 37 would be injected either early in the compression event, preferably approximately between 180 degrees and 60 degrees BTDC, as described below, or later in the compression event near TDC.

By injecting the fuel 37 early in the compression event, it is much more thoroughly mixed with the fuel/air mixture received from the intake duct than would be the case for a diesel engine, thus ensuring a more desirable combustion process, in particular the fuel will burn at a leaner equivalence ratio which results in much lower NOx emissions. The start or initiation of the combustion of the fuel/air mixture received from the intake duct may be varied by controlling the quantity of fuel 37 injected. For instance, an earlier combustion event may be achieved by increasing the quantity of fuel 37 while the timing of the combustion event may be delayed by decreasing the quantity of fuel 37 injected.

By injecting the fuel 37 later in the compression stroke, that is near TDC, conventional diesel fuel injection systems can be used. This approach could be combined with the introduction of one or more additional types of fuel in the intake manifold to achieve an HCCI mode of operation. In particular, the fuel injected into the intake manifold would have a higher λ (i.e. a leaner excess air ratio) and the fuel would burn by autoignition rather than along a flame front as occurs in a conventional dual engine.

Conventional "dual fuel" engines also operate on both a gaseous fuel mixture and diesel fuel. However, conventional dual fuel engines utilize the timing of the injection of diesel fuel to control the start of combustion of the fuel/air mixture received from the intake duct. In order to achieve this result, dual fuel engines inject the diesel fuel at approximately top dead center. In addition, the quantity of diesel

fuel injected in a dual fuel engine is sufficient to ensure that the gaseous fuel in the combustion chamber ignites and burns virtually completely. As a result, dual fuel engines produce emissions similar to most conventional diesel and natural gas engines. In particular, in known dual fuel engines using diesel fuel and natural gas at high load, only a small amount of diesel fuel is required to start ignition and the emissions produced would be similar to a spark ignited natural gas engine. Under other conditions when substantial diesel fuel is injected, the emissions produced would be similar to a conventional diesel engine. The HCCI engine of the present invention, on the other hand, promotes substantially thorough pre-mixture of the diesel fuel with the intake gaseous fuel mixture and controls the timing and quantity of diesel fuel injection to optimize the autoignition and burning of the gaseous fuel mixture while also minimizing emissions. Of course, if desired, the present engine could be operated on diesel fuel only as a conventional diesel engine, or as a modified diesel engine with diesel fuel being injected earlier in the compression event than the conventional diesel engine.

The timing of the start of combustion and the combustion rate in an HCCI engine primarily depend on the temperature history; the pressure history; fuel autoignition properties, i.e. octane/methane rating or activation energy, and trapped cylinder charge air composition (oxygen content, EGR, humidity, equivalence ratio etc.). The present invention presents a structured approach to affecting these variables in such a way that the start of combustion and/or the combustion rate (heat release rate) can be controlled through various combinations of features discussed more fully hereinbelow. The various control features for controlling the start of combustion and the combustion rate are controlled/varied to ensure optimum combustion throughout engine operating conditions so as to achieve low NOx emissions and high efficiency. Application of these control features will cause combustion to occur within a preferred crank angle range relative to the top dead center position of the engine piston. Specifically, applicants have recognized that substantially all of the combustion event

should occur between 20 crank angle degrees before top dead center (BTDC) and 35 crank angle degrees after top dead center (ATDC). Also, combustion would be initiated, preferably between 20 crank angle degrees BTDC and 10 crank angle degrees ATDC, and ideally, approximately between 10 degrees BTDC and TDC. In addition, the duration of the combustion event will typically correspond to a crank angle in the range of 5 - 30 crank angle degrees. Preferably, however, one or more of the control features listed below will be controlled to prolong the duration of combustion to approximately 30-40 degrees to achieve desirable peak cylinder pressures and reduced noise. Thus, optimal control of one or more of the following features will effectively control the start of combustion and/or the rate of combustion such that substantially all of the combustion event occurs between 20 crank angle degrees BTDC and 35 crank angle degrees ATDC. Of course, there may be conditions under which the start of combustion occurs outside the above-stated crank angle range and/or the duration of combustion in the homogeneous engine occurs over a broader crank angle range, or may extend beyond the ATDC limit described above.

Generally, the control variables listed below may be classified in four categories of control: temperature control; pressure control; control of the mixture's autoignition characteristic; and diluent control. Specifically, there are five important control variables which can be used to most effectively control the commencement of combustion and the combustion rate so as to ensure that substantially all of the combustion process occurs within the optimal crank angle limit, i.e. 20 degrees BTDC through 35 degrees ATDC while minimizing emissions and maximizing efficiency. These five control features are as follows:

1. Variable effective compression ratio: By varying the effective compression ratio, both the temperature and the pressure histories can be controlled. Increasing the effective compression ratio advances the combustion event. Decreasing the effective compression ratio retards it.

- The effective compression ratio can be varied by varying the geometric compression ratio, i.e. using a control mechanism to vary the physical dimensions/shape of the combustion chamber.
- The effective compression ratio can be varied with variable valve timing.

For certain purposes, the compression ratio may range from 24:1 (to promote cold starting) to 12:1 (to permit control over the start of combustion and limit the peak combustion pressures). The range of compression ratios would depend on, among other factors, the type of fuel used (more specifically its autoignition properties) for example natural gas or propane.

2. Varying the intake temperature: By varying the intake temperature the combustion event can be advanced or retarded. Increasing the intake temperature will advance the start of combustion, decreasing the intake temperature will retard the start of combustion. This could be done using heat exchangers or burners. For example, a charge air cooler may be positioned along the intake manifold. A burner or heater in combination with a cooler offers exceptional intake temperature control. The exhaust products of the burner may be directly mixed with the intake air, the burner could use the intake air directly for its air supply, or the heat generated by the burner could be added to the intake air through a heat exchanger.

3. Changing the octane or methane number of the fuel: By mixing two or more fuels, or by mixing the fuel with an additive, it is possible to vary the octane or methane number of the charge. This makes it possible to retard or advance the combustion event. For example, a fuel which tends to autoignite more readily could be controllably mixed with a fuel that tends to autoignite less readily (or a fuel that ignites at a high temperature and a fuel that ignites at a low temperature could be used) to enable direct control over the timing of ignition and rate of combustion by changing the ratio of the fuels that are present in the combustion chamber during the combustion event.

4. Charge dilution: By adding a liquid or gas diluent, for example by injecting water, uncooled or cooled exhaust products, or air (either into the intake air or directly into the charge in the cylinder), it is possible to retard the combustion event.

5. Varying boost: The time of autoignition is closely related to the ignition delay. The ignition delay, in turn, has been shown to be a function of pressure. By varying the boost pressure, the start of combustion can be controlled. In a typical application, for a constant torque condition, the fuel flow rate would remain virtually constant, and the boost pressure would be increased to advance the start of combustion or decrease the boost to retard the start of combustion. For example, an air compressor, a turbocharger, a supercharger such as driven by an engine power take-off, or an electrically powered compressor, could be used.

Other methods or features for variably controlling the initiation of combustion and the combustion rate are as follows:

6. Varying in-cylinder temperature distribution: By varying the in-cylinder temperature distribution, the start of combustion and/or the overall combustion rate can be positively affected. Some ways to do this are:

- Using split ports where some of the incoming air fuel mixture is warmer/colder than the rest of the incoming mixture
- Introducing hot spots in the cylinder
- Using a glow plug
- Varying the temperature of the combustion chamber walls (i.e. the wall temperature of the cylinder liner, piston and/or engine head) by varying, for example, the temperature of the engine coolant, the temperature of the engine oil or the rate of cooling of the combustion chamber walls.

7. Varying the engine speed: The time of autoignition depends on the temperature and pressure histories. By changing the engine speed, these histories are

changed. It is possible to advance the combustion event by reducing the engine speed, and to retard the combustion event by increasing the engine speed. One example where this could be used is in an application where the engine drives a generator or alternator.

8. Regenerator: A regenerator (similar to that used in a Stirling engine) could be used to recover and transfer exhaust heat into the intake air through a heat exchanger thereby controlling the intake temperature.

9. Varying the surface to volume ratio in the combustion chamber: The temperature and pressure histories are sensitive to the heat transfer. Varying the surface to volume ratio in the combustion chamber can change the heat transfer and can be used to control the combustion.

10. Exhaust gas recirculation (EGR): EGR can increase the temperature of the incoming air fuel mixture and thus can be used to control combustion.

11. Opposed piston engine with variable crank phasing: By using an opposed piston engine with variable crank phasing, the effective compression ratio, as well as the volume vs. crank angle relationship, can be changed.

12. In-cylinder gas injection: By injecting a gas, i.e. air, nitrogen, carbon dioxide, exhaust gas, etc., into the cylinder, the temperature and the temperature distribution in the cylinder can be altered. These can be used to control the start of combustion and the combustion rate.

13. Variable charge stratification: By varying the level of charge stratification, the temperature and equivalence ratio distribution can be altered to permit control of the combustion rate and/or the start of combustion.

14. Fuel additive to change autoignition characteristics of fuel: By adding a controlled amount of a fuel additive (and/or small amounts of propane, ethane, or other hydrocarbons) the autoignition properties of the fuel can be changed to advance or retard the start of combustion.

15. Any way to change the fuel octane rating or activation energy: Any method that changes the fuel's octane/methane number or the activation energy of the fuel can be used to advance/retard combustion.

16. Varying exhaust manifold back pressure: The residual mass fraction is sensitive to the exhaust manifold back pressure. By increasing the exhaust back pressure, the residual mass fraction can be increased thus increasing the temperature of the charge which, in turn, advances combustion. Another technique for varying the residual mass fraction would be by varying the valve timing. Also, by adding exhaust products while maintaining the temperature of the charge by, for example, injecting a cooling diluent, such as air and/or water, the combustion rate can be slowed thus increasing the combustion duration and retarding combustion.

17. Vary oxygen concentration in intake air: It has been shown that increasing the oxygen concentration decreases the ignition delay. Therefore, combustion may be controlled by modifying the oxygen concentration of the intake air. This may be done by adding oxygen (or an oxygen rich gas mixture) to the intake or by selectively removing nitrogen from the intake air (using a membrane for example).

18. Using a prechamber, plasma jet or a fuel injector to increase pressure and temperature in the main combustion chamber: Increasing the temperature/pressure in this manner would advance the start of combustion. Such a device would also lead to ignition of some of the charge. The heat released by this part of the charge would further increase the temperature and pressure allowing the remainder of the charge to autoignite earlier.

19. Varying in-cylinder surface temperatures: Increasing surface temperatures will cause lower heat transfer to the combustion chamber surfaces which will advance combustion. Varying in-cylinder surface temperatures can be achieved by varying the cooling effect of the engine coolant and/or the lubricating oil on the cylinder/piston assembly.

In order to provide combustion control capability, the present system also includes a sensor for detecting a parameter directly related to the start of combustion or the combustion rate. For example, a cylinder pressure sensor may be provided on any or all engine cylinders for sensing, on a cycle-by-cycle basis, the commencement of combustion, for example, by sensing the very rapid increase in the cylinder pressure. Other forms of sensors could be used including accelerometers, ion probes, optical diagnostics, strain gages and/or fast thermocouples in the cylinder head, liner or piston. The sensor would provide the feedback control to an electronic control system which processes the combustion information and generates outputs that will feed control signals to each of the components of the HCCI system of the present invention.

We claim:

1. A homogeneous charge compression ignition internal combustion engine, comprising:

an engine body;

a combustion chamber formed in the engine body;

combustion control means for controlling at least one of the start of combustion, the duration of combustion and the rate of combustion to reduce emissions and optimize efficiency, said combustion control means including at least one of a temperature control means for varying the temperature of the mixture of fuel and air, a pressure control means for varying the pressure of the mixture, an equivalence ratio control means for varying an equivalence ratio of the mixture and a mixture autoignition property control means for varying an autoignition property of the mixture;

engine operating condition detecting means for detecting an engine operating condition indicative of one of the start of combustion, the rate of combustion and the duration of combustion and generating an engine operating condition signal indicative of said engine operating condition; and

processing means for receiving said engine operating condition signal, determining at least one of a start of combustion, rate of combustion and duration of combustion value based on said engine operating condition signal, and generating one or more control signals based on said at least one of a start of combustion, rate of combustion and duration of combustion value, said one or more control signals controlling at least one of said temperature control means, said pressure control means, said equivalence ratio control means and said mixture autoignition property control means to variably control at least one of the start of combustion, the rate of combustion and the duration of combustion.

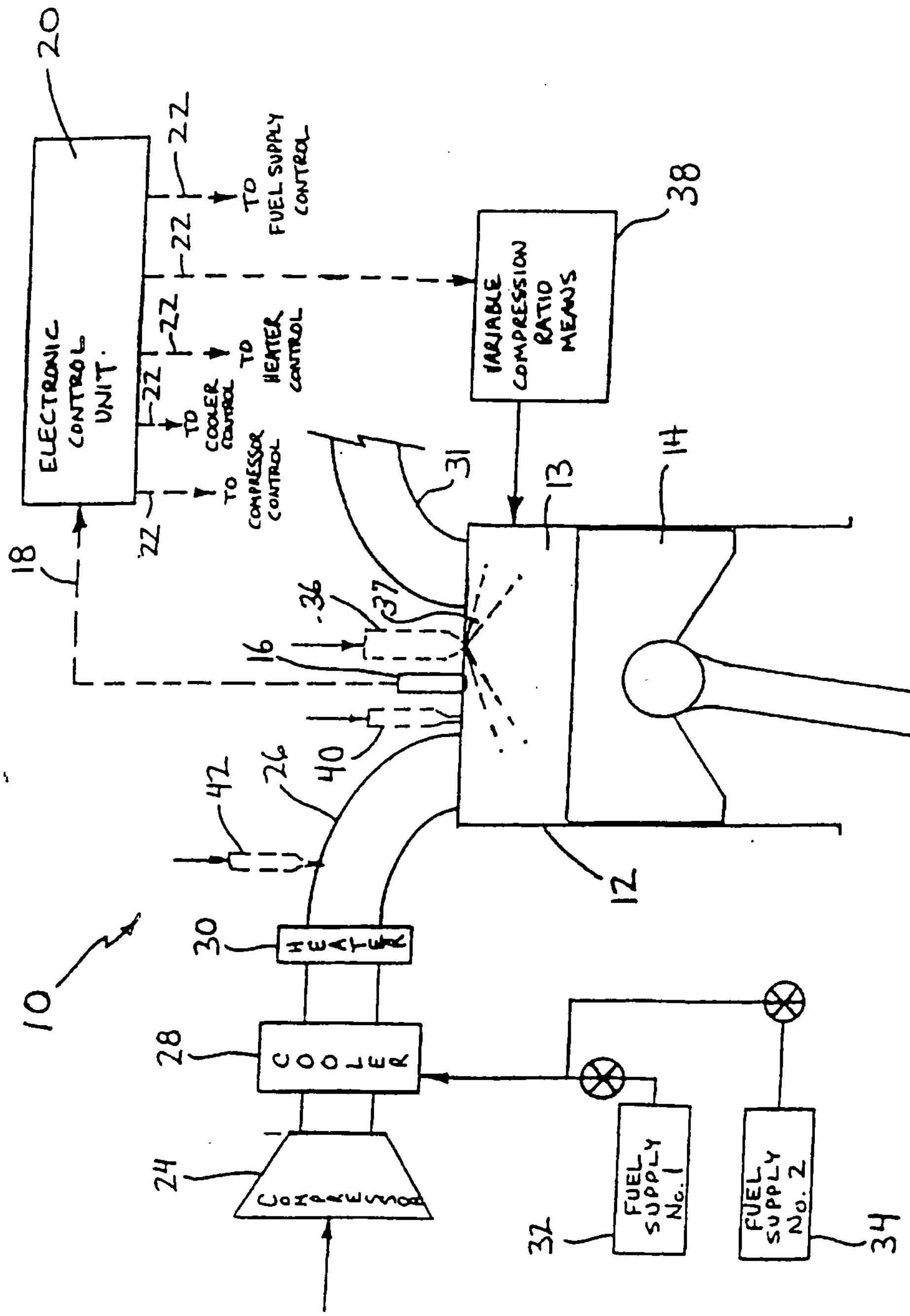
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FIG. 1